PIP-II Cryomodules Overview

Genfa Wu on behalf of PIP-II Cryomodule Team

PIP-II Fine Tuning Workshop at CEA/Saclay

25-26 June, 2018

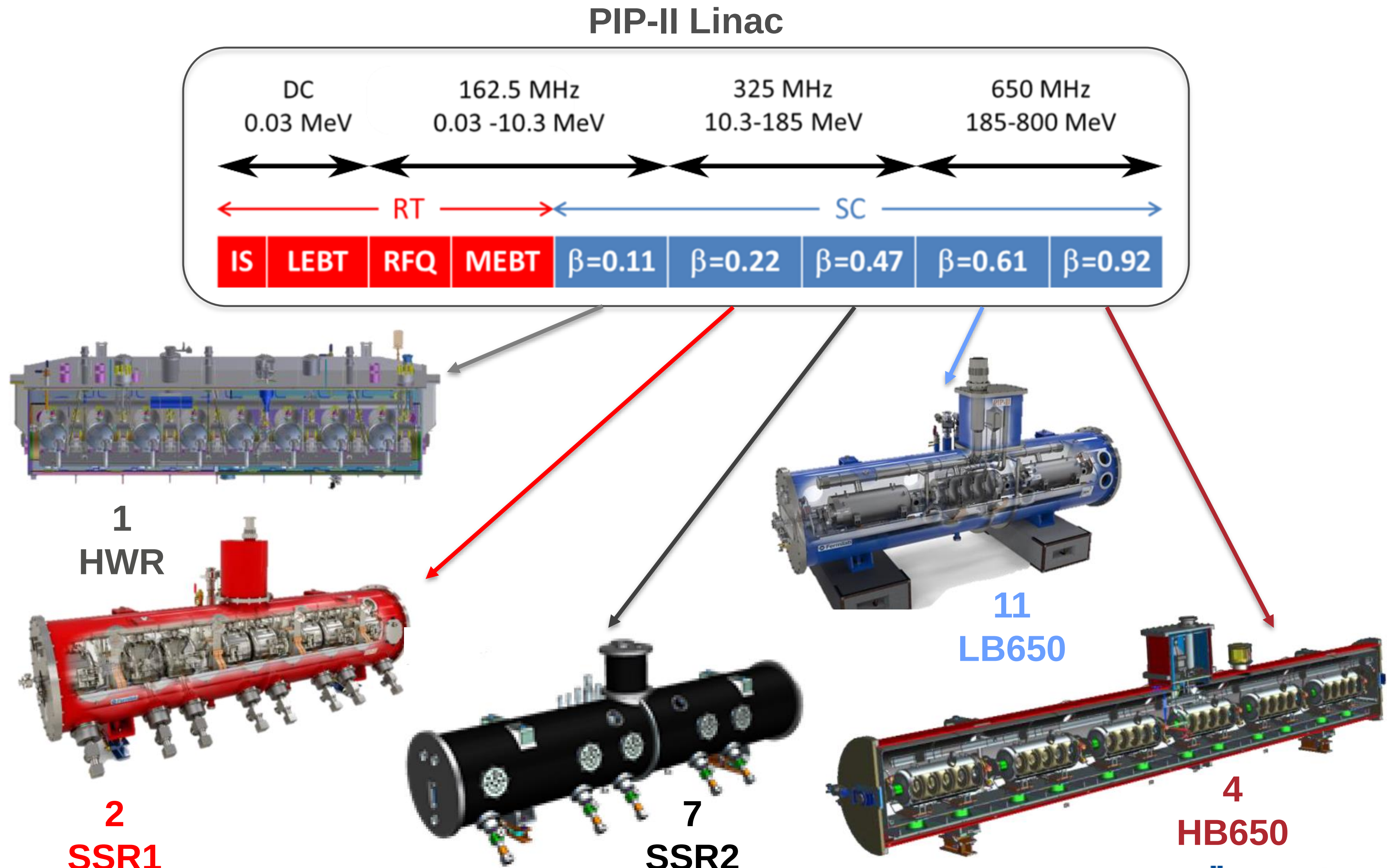
Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

PIP-II Cryomodules Layout



Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Cryomodule Design Overview

Cryomodule	Number	Cavity Number	Magnet Number	Style	Note
HWR	1	8	8	"Bath Tub" Style	ANL Led Design
SSR1	2	8	4	Strong back support in circular tube	FNAL Led Design
SSR2	7	5	3	Strong back support in circular tube	Integrated Design
LB650	11	3	0	Strong back support in circular tube	Integrated Design
HB650	4	6	0	Strong back support in circular tube	FNAL Led Design
Total	25	116	37		

Quadrupole doublets are outside and between 650 MHz cryomodules

Cryomodule Design Considerations

- Primary Design Features
  - Room temperature lower strong back support
  - Fully segmented – individual cryogenic feed/return, individual insulating vacuum
  - Side-mounted cryogenics feed and control box
  - Integrated thermal shield in cavity support base
  - Tuner access ports
  - Individual RF sources/RF Coupler/SRF cavity
  - Simplified string assembly
    - Fixed high power coupler
    - No HOM couplers
  - Robust mechanical design for transportation
    - Lessons learned from LCLS-II

Cryomodule Design Considerations

- Standardization
  - Common cryogenic circuit
  - Common instrumentation strategy
  - Common alignment strategy
  - Shared components
    - Same coupler, tuner, interface for 325 MHz spoke resonator cryomodules
    - Same coupler, tuner, interface for 650 MHz elliptical resonator cryomodules

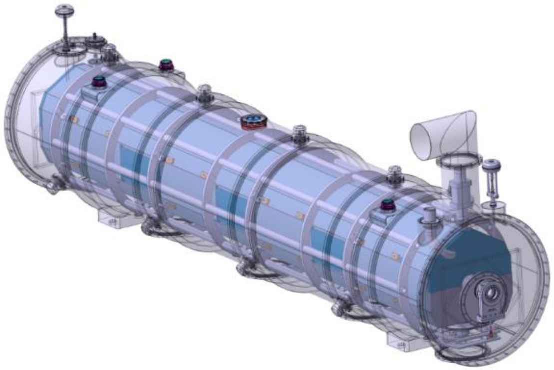
- Design uniformity kept to the extent practical
  - Facilitates CM assembly and repairs

Outline

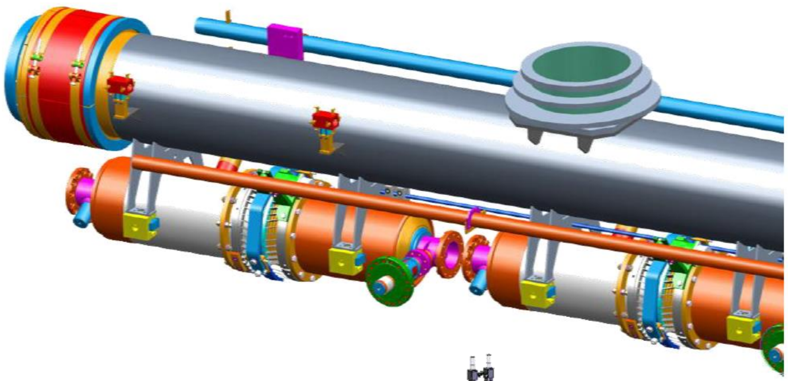
- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Modern Design of Cryomodule Mechanical Support

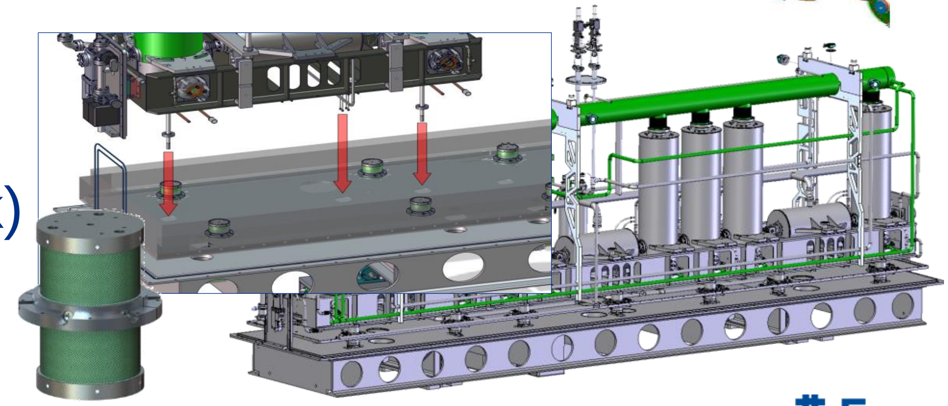
- Spaceframe Design
  - CEBAF, SNS, ESS



- Top Support
  - TTF, XFEL, ILC, LCLS-II



- Bottom Support
  - FRIB, PIP-II (strong back)

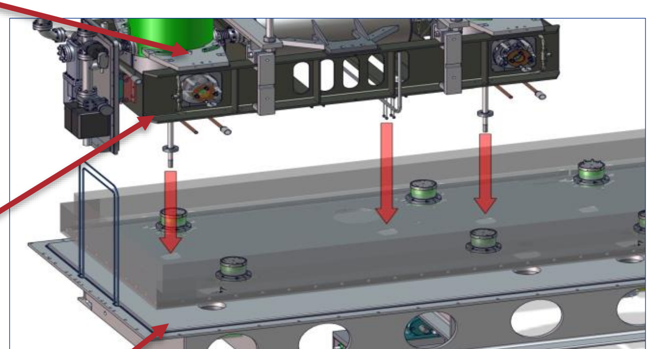


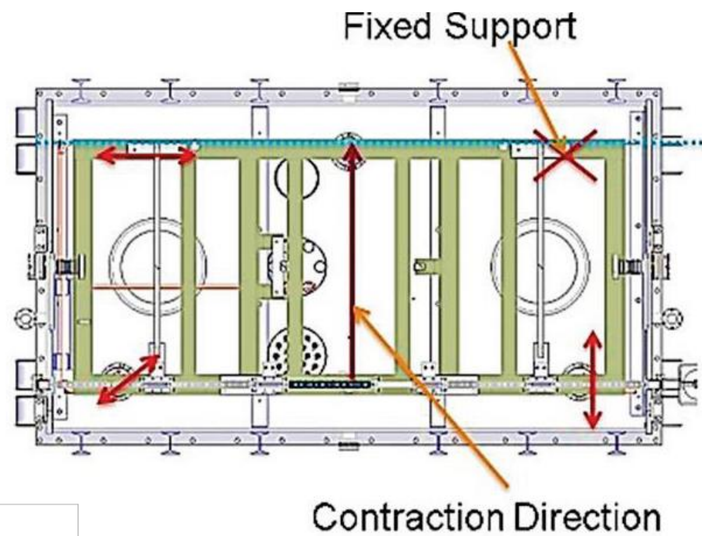
FRIB Alignment

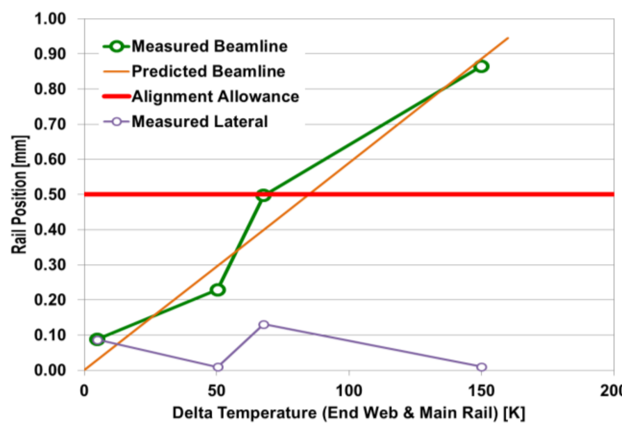
2K Cavity Fixed to rail support

45 K Rail Support With G-10 support post

Room temperature base plate



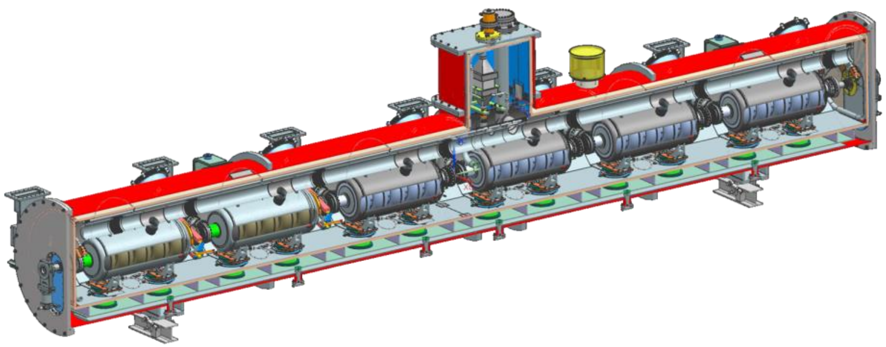


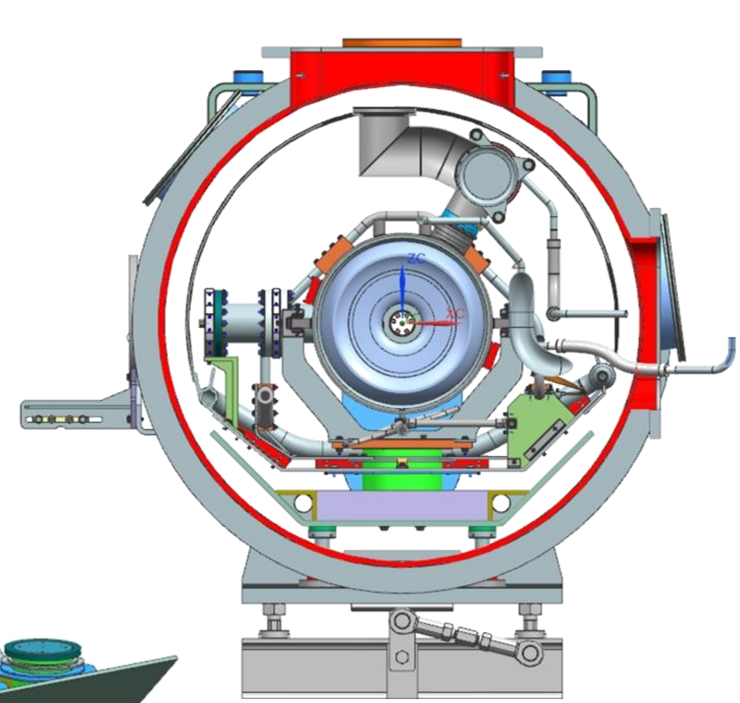


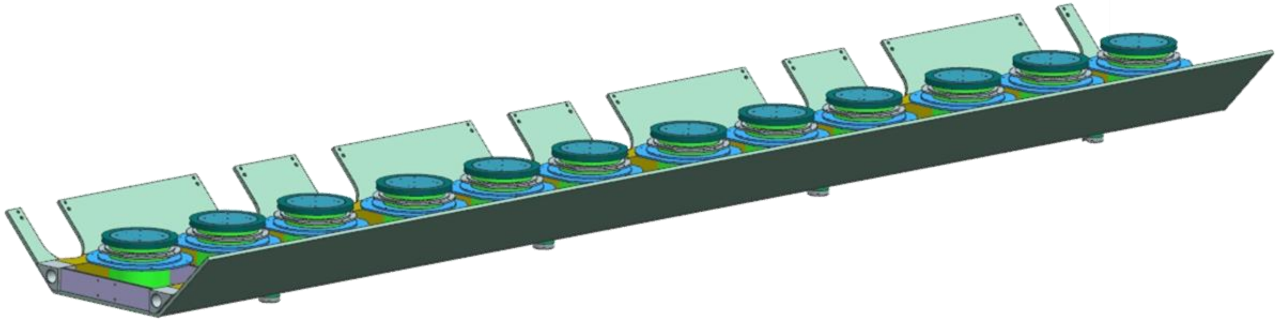
FRIB Support Alignment has been demonstrated

M. Leitner et al., Proceedings of SRF2013, Paris, France, MOIOA01

Alignment Configuration





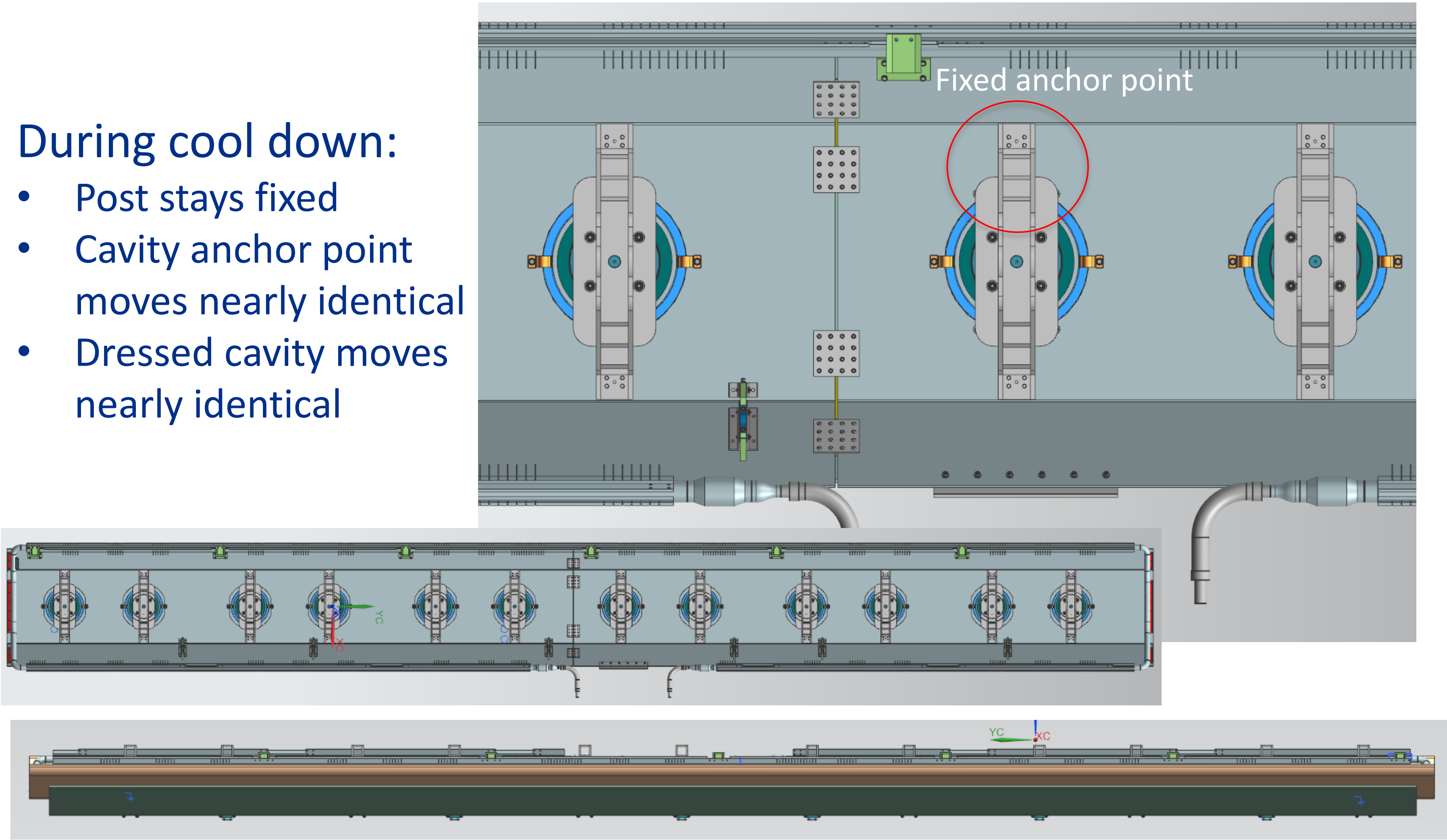


- Warm Strong back support
- Adjustable C-clamps, not accessible after assembly

Alignment Configuration

During cool down:

- Post stays fixed
- Cavity anchor point moves nearly identical
- Dressed cavity moves nearly identical



Fermilab PIP-II

Alignment

	Transverse (rms in mm)	Angle (rms in mrad)	Note
HWR Cavity	0.5	2	
HWR Solenoid	0.5	1	
SSR Cavity	1	10	
SSR Solenoid	0.5	0.5	
650 MHz Cavity	0.5	1	No magnet

Alignment Monitoring

Monitor after assembly, during transport and cool down.

- Optical Wire Target
- Wire Position Monitor
- Brandeis Camera Angle Monitoring (BCAM)

- To be determined

S. Zorzetti

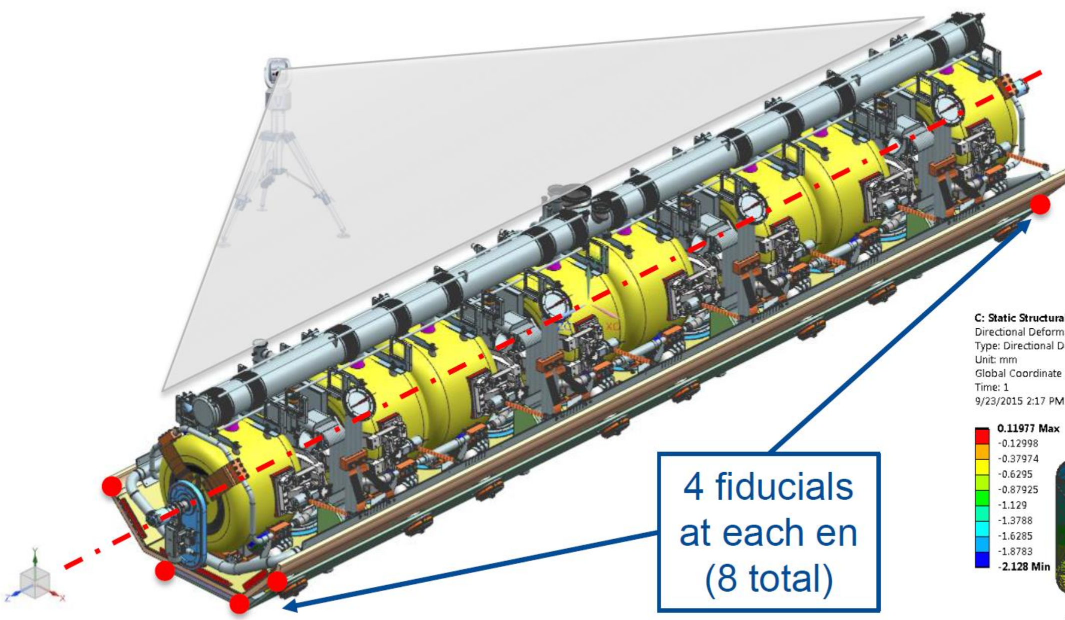
SSR1 Alignment Implementation

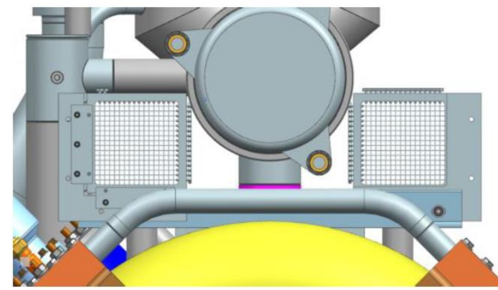
Final alignment of the key-components

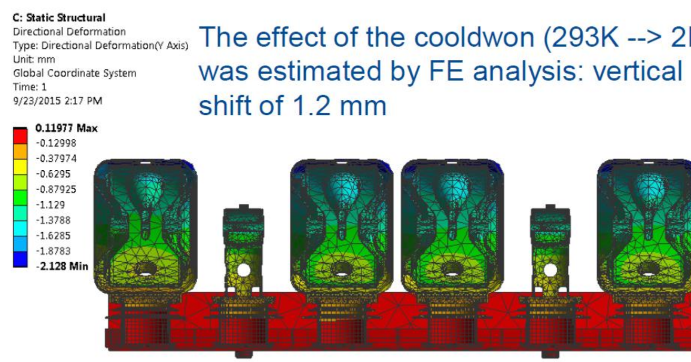
Laser trackers will be used to:

- **Final alignment of cavities and solenoids** within the PIP-II alignment requirements, including the shifts due to cooldown.
- Identify the position of the **electric center of BPMs** by scanning the body OD.
- Fiducialization of the key components axis to accessible targets on the support.

Install and calibrate the wire targets on each key-components.





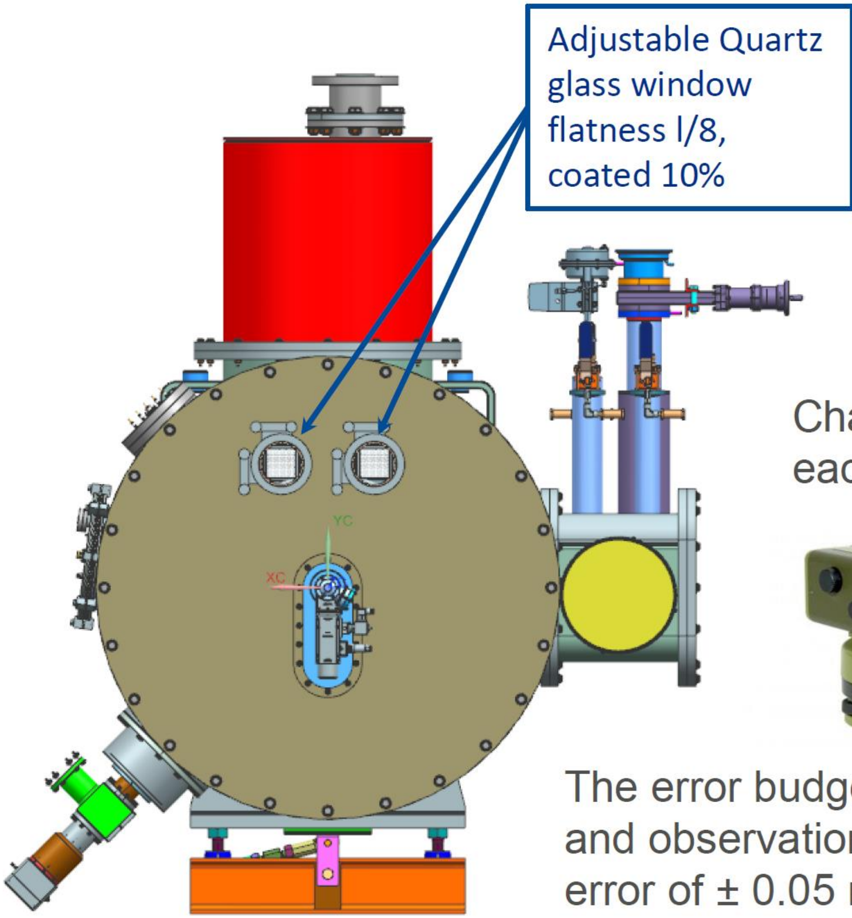


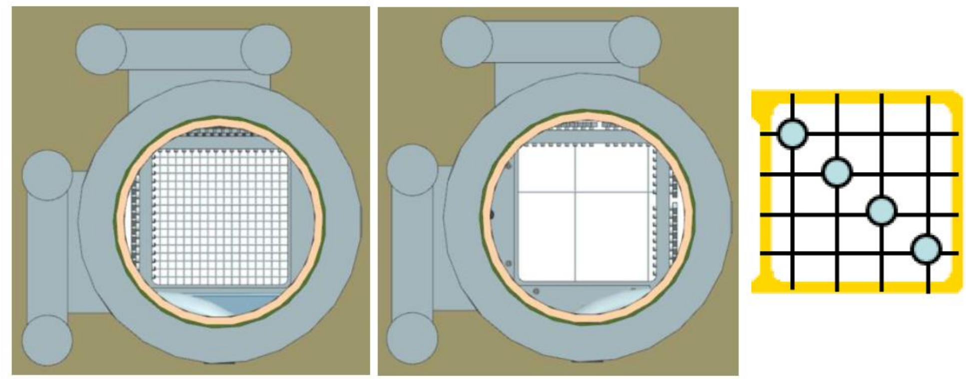
The effect of the cooldwon (293K --> 2K) was estimated by FE analysis: vertical shift of 1.2 mm

Slide by D. Passarelli

SSR1 Alignment Implementation

Changes in alignment due to shipping and handling or during cooldown and operation will be monitored using a series of wire targets on each cavity and solenoid, viewed through optical windows in either end of the cryomodule assembly.





Changing focal point from ∞ to 0 we can localize each wire target with the use of optical instruments:

Wild N3 precision level

Bronson RH190 precision Telescopic Transit

The error budget analysis based on optical instruments specs and observation procedure shows an estimated measurement error of ± 0.05 mm - 0.15 mm (distance dependent)

Slide by D. Passarelli

Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Documentation Structure

- PIP-II Project Goals and Key Performance Parameters
- GRD – Global Requirement Document
- SCD – System Configuration Document
- FRS – Functional Requirement Specification
- ICD – Interface Configuration Document
- TRS – Technical Requirement Specification
- Technical Design Report
- Review Standardization (PDR, FDR, PRR, Results Review, Transportation Review)
- Production Documents
  - Procedures
  - Travelers
  - Test Reports, QA and NCR Documents
  - Hold Point Data Review

See A. Klebaner Presentation

- DCR – Design Change Request

Cavity Interface - Mechanical

Example: HB650

	Qty	Unit	Note
Cavity Temperature	2	K	
Cavity Helium Vessel Pressure	23	Torr	
Helium Pressure Stability	0.1	Torr	
Cavity Vacuum (Warm)	<1e-7	torr	
Dressed Cavity Length	1,400	mm	
Beampipe Aperture Diameter	118	mm	
Longitudinal Stiffness	<5	kN/mm	
Helium Return Port	1		
Helium Cool Down Inlet	2		Allow fast cool down
Support Lug	4		
Dressed Cavity Weight	134	kg	Not including Tuner,coupler.
Helium Volume	0.073	m3	

Cavity Interface - RF

Example: HB650

HB650	Qty
Operating mode	CW with pulsed capability
Cavity beta	0.92
Cavity Number in Cryomodule	6
Nominal Gradient [MV/m]	17.8
Q0	(3-4)e10
Cavity Pressure Sensitivity [Hz/mbar]	<25
Lorentz Force Detuning [Hz/(MV/m)^2]	<1
Coarse Tuning range/resolution [Hz]	200,000/2
Fine Tuning range/resolution [Hz]	1,000/0.1
Tuning Sensitivity [kHz/mm]	<5
RF Power CW [kW]	64

Cavity Interface - Instrumentation

Example: Subset of Production HB650 Cryomodule

- Cavity Field Probe
- Tuner Step Motor Control
- Tuner Piezo Control
- Cavity Coupler Flange Temperature Sensor
- Helium Vessel Temperature Sensors (top and bottom)
- Helium Vessel Heater
- Magnetic Field Sensors (Two sensors at Cavity location #1,3,4,6)
  - More if low cost non-fluxgate sensors are available
- Cavity Vacuum

Cavity Interface - Instrumentation

Example: Subset of **Prototype** HB650 Cryomodule

- 4 Cavity Beam Pipe Temperature Sensors
- 4 Temperature Sensors inside of Helium Vessel (2 top sensors, 2 bottom sensors) for each of Cavity Location #1,3,4,6
- 2 Fluxgate Sensors inside of Helium Vessel for each of Cavity Location #1,3,4,6
- Low cost magnetic field sensors on each cavity beampipe if available

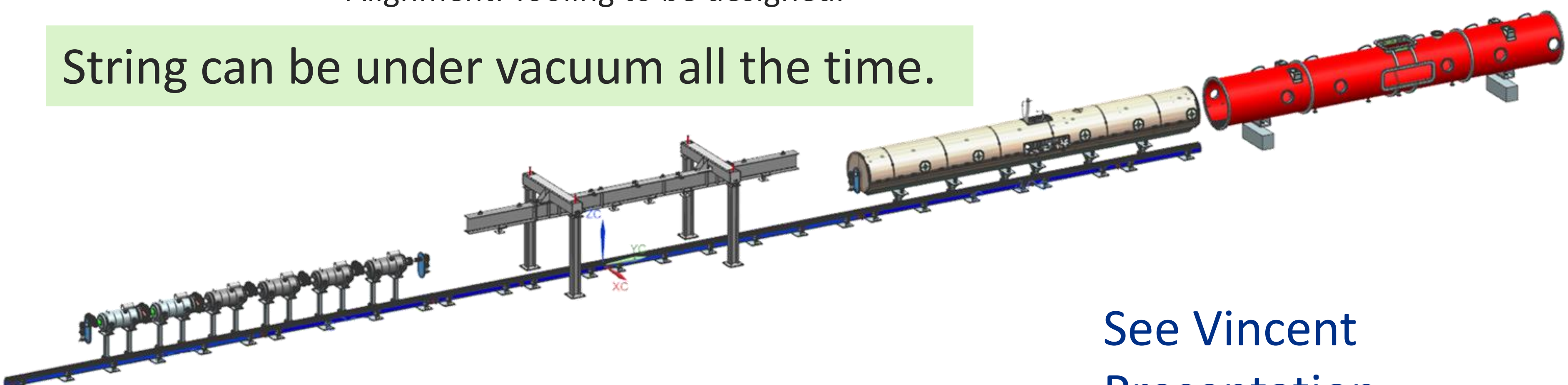
Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Assembly Tooling

- Workstation 0: Coupler assembly (similar to LCLS-II). Tooling scaled from LCLS-II
- Workstation 1: Cavity string assembly (similar to LCLS-II). Tooling scaled from LCLS-II
- Workstation 2: Lift a cavity string up to a support frame tooling
  Instrumentation, helium pipe, strong back support assembly
  Lift onto the strong back support assembly (different from LCLS-II)
- Workstation 3: Assembly of the cold-mass: magnetic shield, tuner, thermal straps, MLI, thermal shield, alignment (similar to LCLS-II). Tooling to be designed
- Workstation 4: Insertion of the cold-mass in the vacuum vessel (different from LCLS-II, no cantilever). Tooling similar to SSR1
- Workstation 5: Completion of the cryomodule: warm coupler installation, cryogenic circuit. Alignment. Tooling to be designed.

String can be under vacuum all the time.



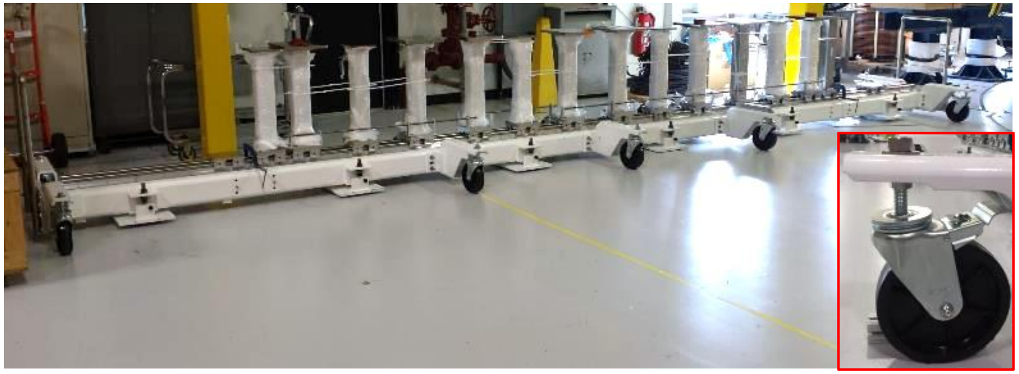
See Vincent Presentation

Stephane Berry Visit in March/April 2018

- Organization and integration of SSR1 activities in the Lab2 cleanroom
- Qualification of tooling and procedures to be used for the SSR1 string assembly.
- Evaluation and recommendation for future improvements of the cleanroom

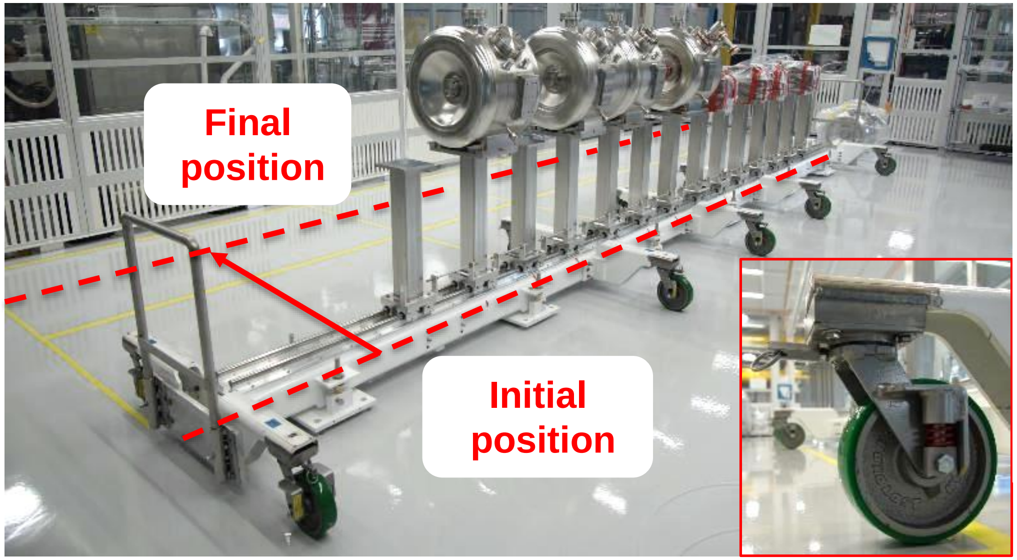
Fermilab is greatly thankful for CEA/Saclay's support and Stephane helped Fermilab to improve both PIP-II and LCLS-II

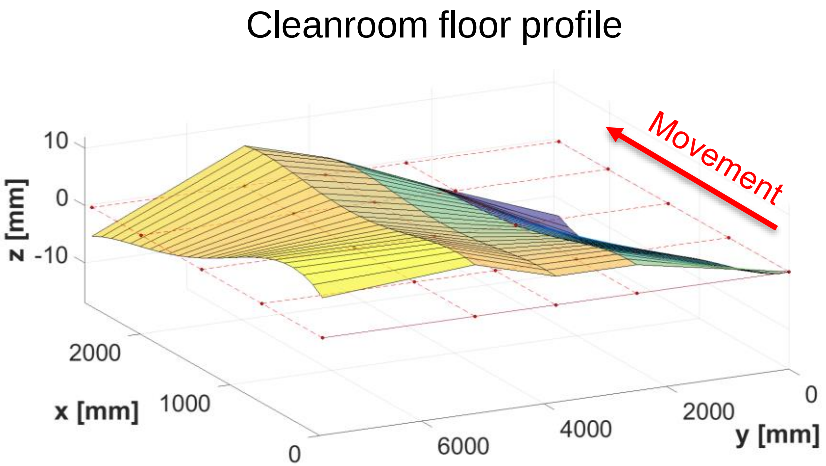
Preparation of the SSR1 string assembly dry-run



- Wheels were found to be inappropriate because of unexpected uneven floor
- Wheels lose contact with floor during motion leading to the wobbling of the rail system and excessive cavity displacements

- New suspension wheels and stiffer connections were procured
- Measurement of the cleanroom floor profile
- Wheel spring stiffness is optimized to minimize cavity vertical displacement

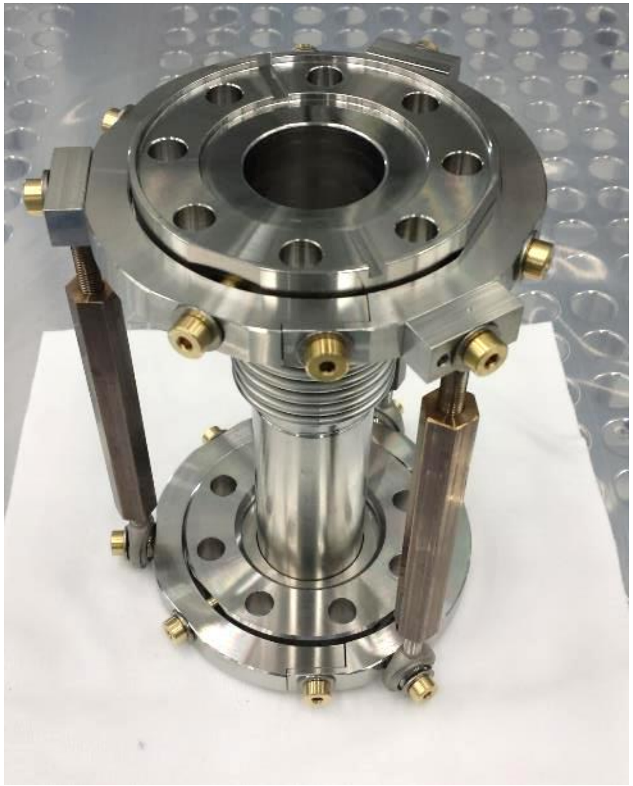




Preparation of the SSR1 string assembly dry-run

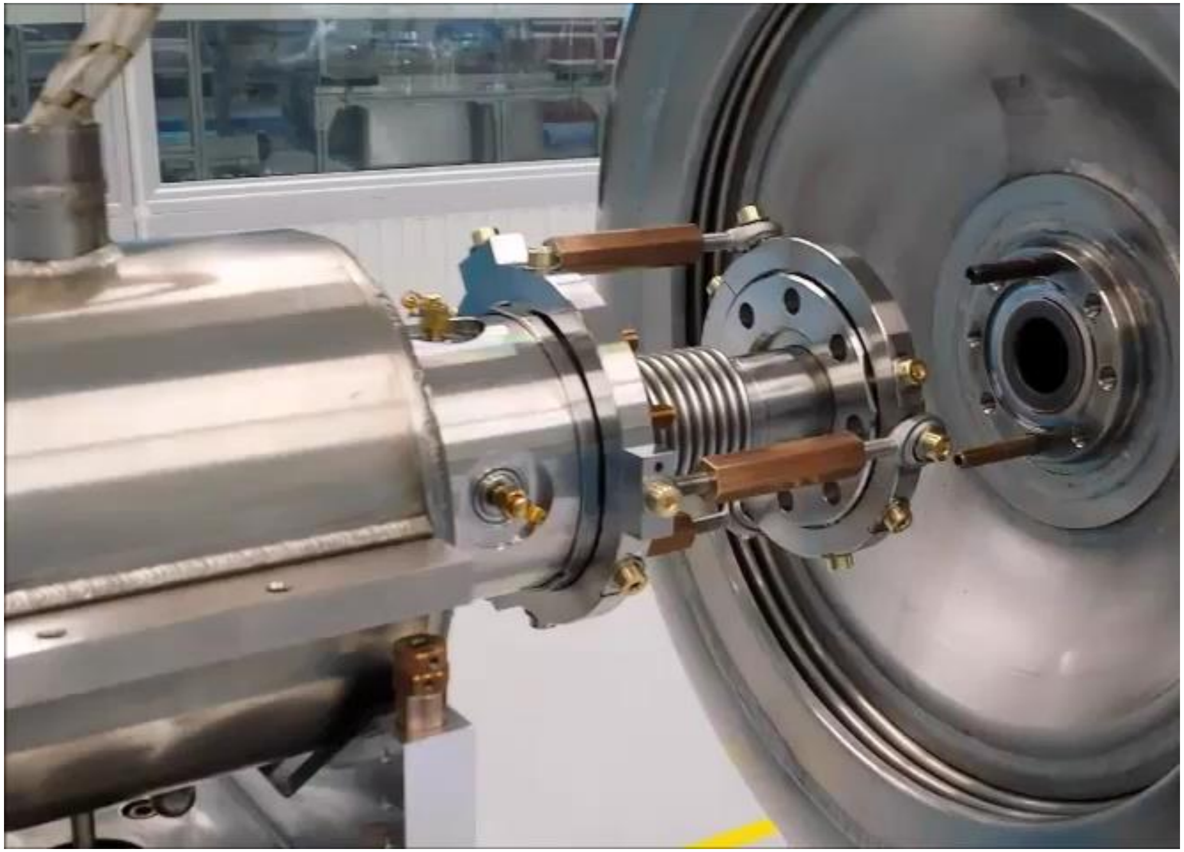
- Dry-run of SSR1 string assembly is carried out on a half cavity string
- The goal is to assess the feasibility of a cleanroom-compatible assembly

Preparation of the SSR1 string assembly dry-run



- ✓ Bellows cages provides 2 rotational degrees of freedom at the end flange
- ✓ Can be splitted in 2 halves so that can be removed prior cryomodule assembly

Preparation of the SSR1 string assembly dry-run



✓ Sub - millimeter precise and reliable alignment

✓ Easy to use system

Link

Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

Heat Load – Nominal

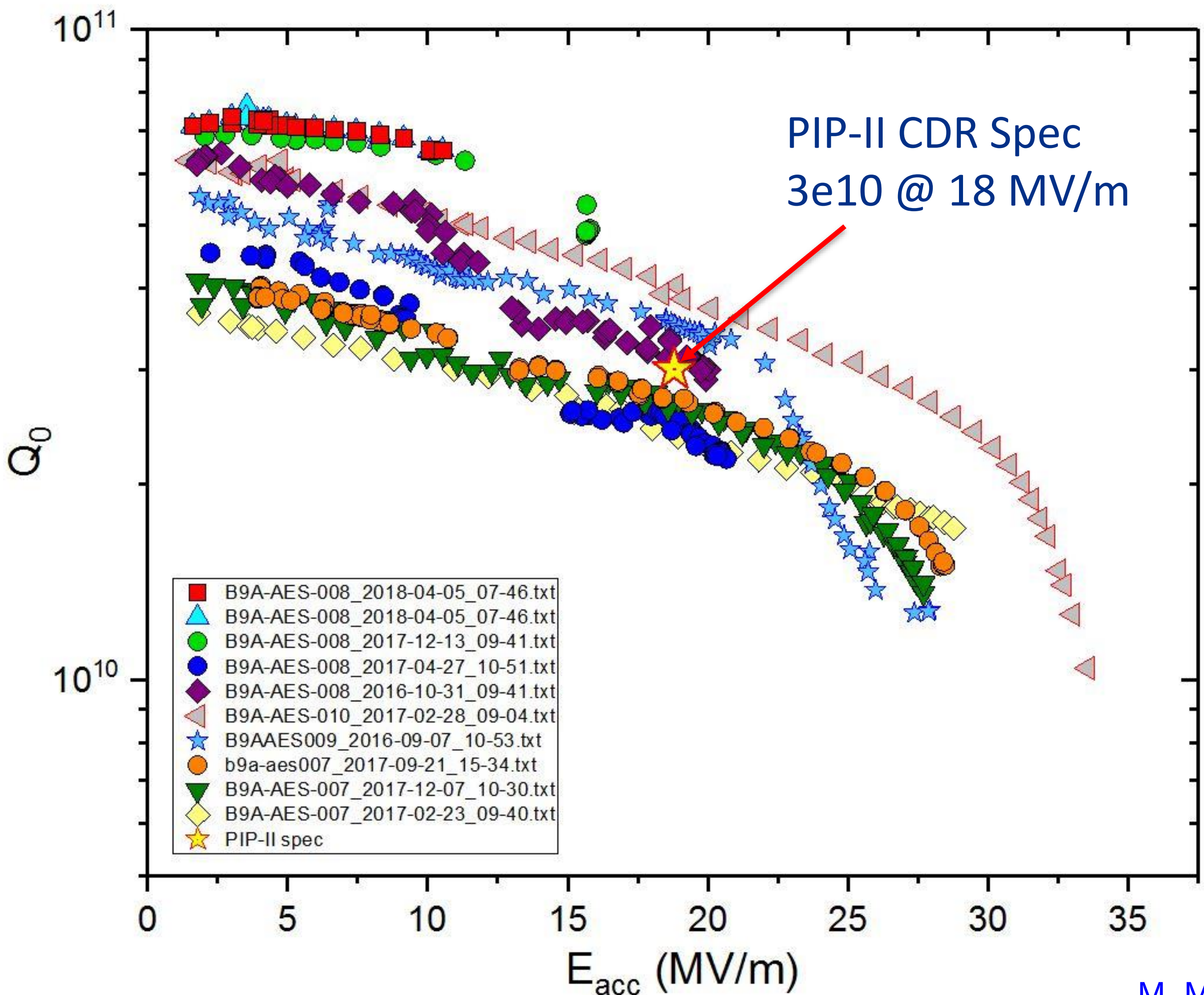
	HWR	SSR1	SSR2	LB650	HB650
Cavity length	0.207	0.205	0.438	0.74	1.1185
R/Q	272	242	297	341	610
G	48	84	115	193	260
Nominal Gradient	9.7	10	11.4	15.9	17.8
Nominal Q0	5.0E+09	6.0E+09	8.0E+09	2.2E+10	3.0E+10
Cavity number	8	16	35	33	24
Cryomodule number	1	2	7	11	4
1 Cav Nominal Dynamic Heat Load	3.0	2.9	10.5	18.2	21.7
Total Nominal Dynamic Heat Load	23.7	46.3	367.3	601.6	519.8
Static Heat Load per CM Type	37	26	61.6	44	32
Total PIP-II Static HeatLoad					200.6
Total PIP-II Dynamic HeatLoad					1,558.7
Total PIP-II distribution Heat Load					250
Total PIP-II Cryogenic Heat Load (W)					2,009

Based on CDR

Heat Load – R&D Goal

	HWR	SSR1	SSR2	LB650	HB650
Cavity length	0.207	0.205	0.438	0.74	1.1185
R/Q	272	242	297	341	610
G	48	84	115	193	260
Nominal Gradient	9.7	10	11.4	15.9	17.8
Nominal Q0	5.0E+09	6.0E+09	1.0E+10	3.0E+10	4.0E+10
Cavity number	8	16	35	33	24
Cryomodule number	1	2	7	11	4
1 Cav Nominal Dynamic Heat Load	3.0	2.9	8.4	13.7	16.2
Total Nominal Dynamic Heat Load	23.7	46.3	293.8	451.2	389.9
Static Heat Load per CM Type	37	26	61.6	44	32
Total PIP-II Static HeatLoad					200.6
Total PIP-II Dynamic HeatLoad					1204.9
Total PIP-II distribution Heat Load					250
Total PIP-II Cryogenic Heat Load (W)					1656

Dynamic Heat Load – Cavity Performance



M. Martinello

Dynamic Heat Load – High Q R&D

650 MHz at 18 MV/m

	EP	EP/120C baking	N-doping	N-infusion
Residual resistance [nΩ]		3.5 (assumed)	3.5	
BCS resistance [nΩ]		2.7	1.4	
Magnetic Field Rs sensitivity [[nΩ/mG]		0.3	0.75	
Rs_trapped flux of 1mG [nΩ]		1	0.75	
Total Rs [nΩ]		7.2	5.7	
Q0		3.6e10	4.6e10	

Data is still preliminary and incomplete
Processing procedure is still being optimized

M. Checchin, M. Martinello et al., App. Phys. Lett. 112 072601 (2018)

Dynamic Heat Load – High Q R&D

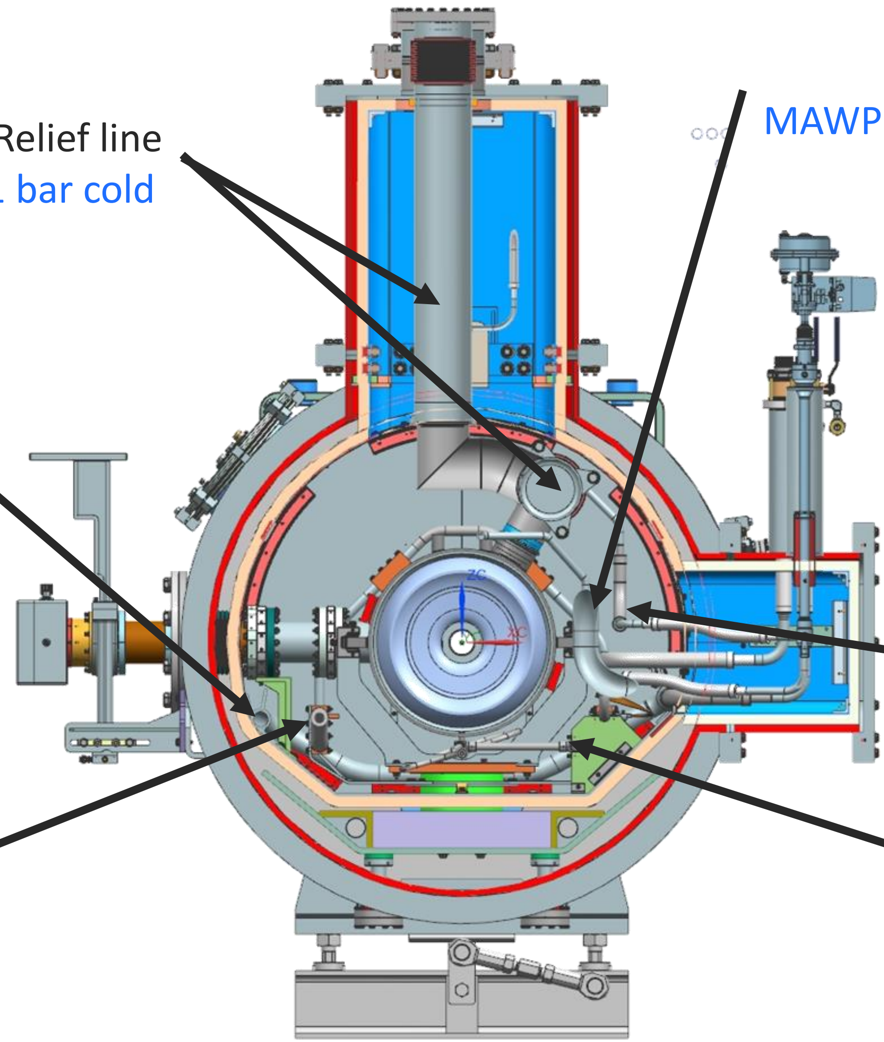
- Cavity processing
  - Reduce residual resistance and BCS resistance
- Improve magnetic shield for large size cavity (Cryomodule)
- Capability to fast cool down to expel flux
  - Cryogenic design (Cryomodule)
  - Material specification and heat treatment

1-cell Cavity Processing → 5-cell Cavity Processing → Horizontal Test of 5-cell dressed cavity → Prototype Cryomodule

Cryomodule Design to Support High Q

- Cryogenic Supports Fast Cool Down
- Cryomodule Thermal Design to Minimize Thermoelectric Current
- Magnetic Shield to Minimize Ambient Earth Magnetic Field
- Better Instrumentation for High Q operation

Cryogenic

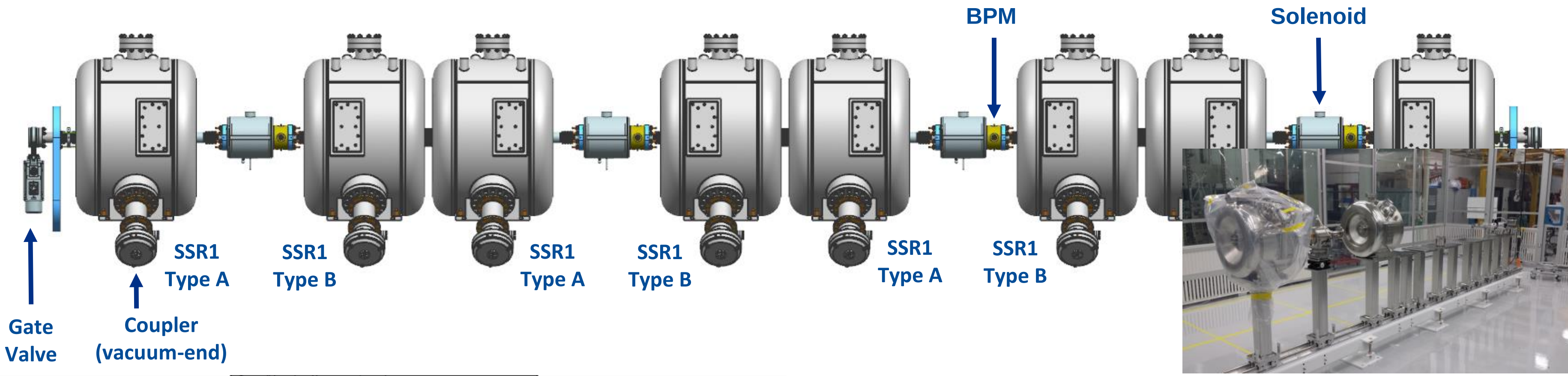


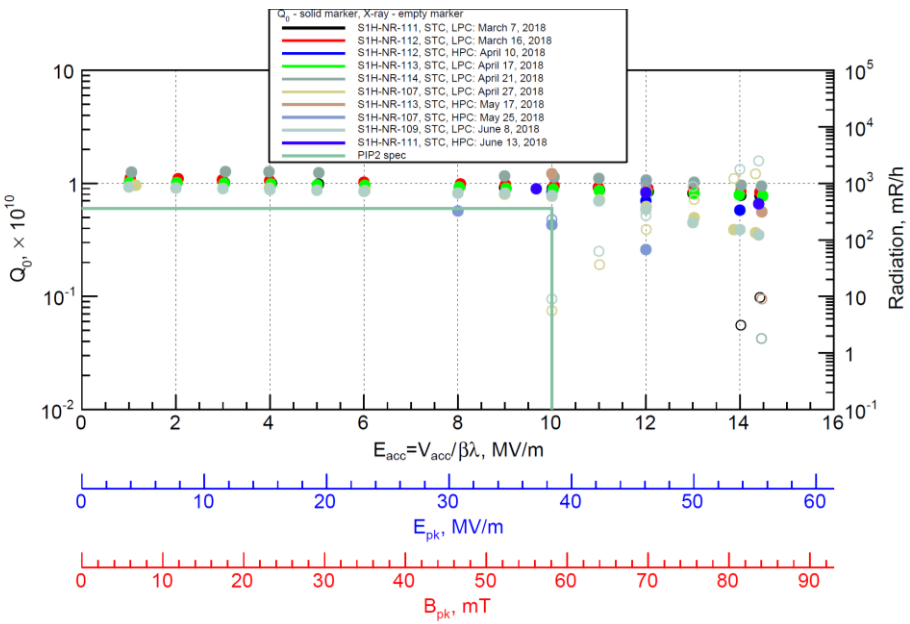
V. Roger

Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

PIP-II SSR1 Cryomodule Progress



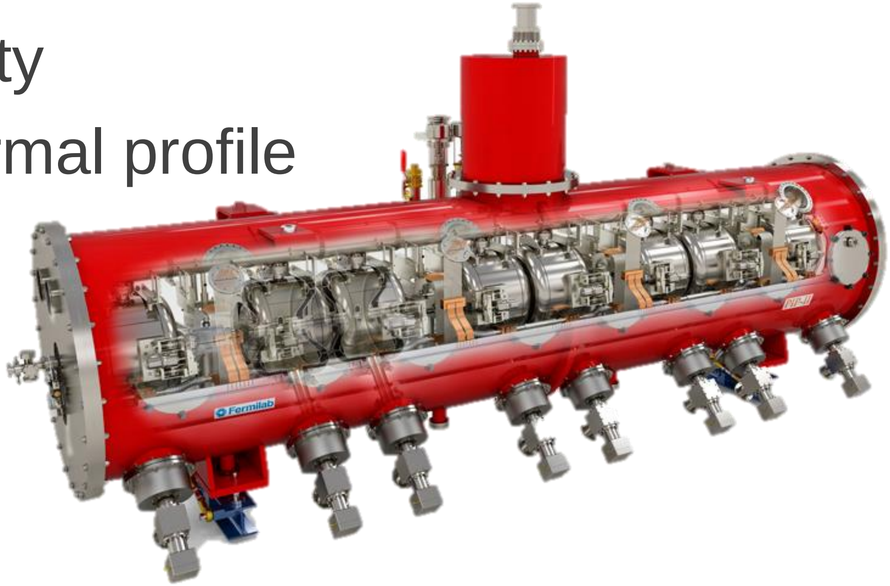


- LAB2 has demonstrated successful operations of a horizontal high pressure rinsing and clean room assembly
- 4 Cavities have been qualified with high power coupler tests
- 4 more cavities are to be qualified in the next two months after power couplers are received

Design Validation

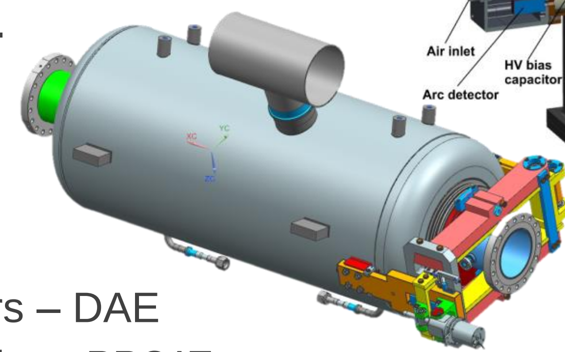
- Strong back support and support post thermal profile
- Cavity alignment change during cool down
- Static heat load of support post
- Coupler alignment change during cool down
- RF performance
- String assembly quality
- Cryogenic Circuit thermal profile
- Microphonics

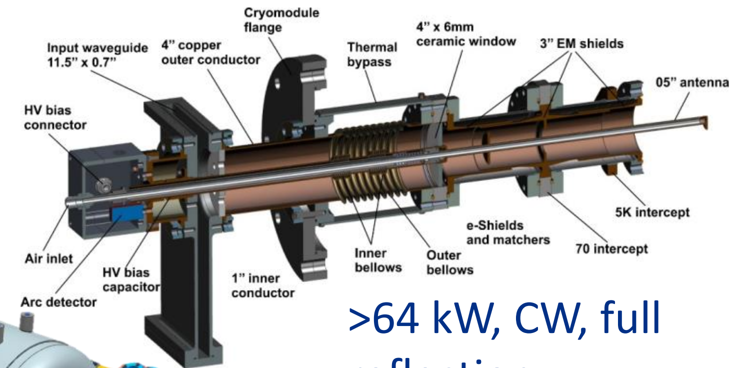
Spring 2019



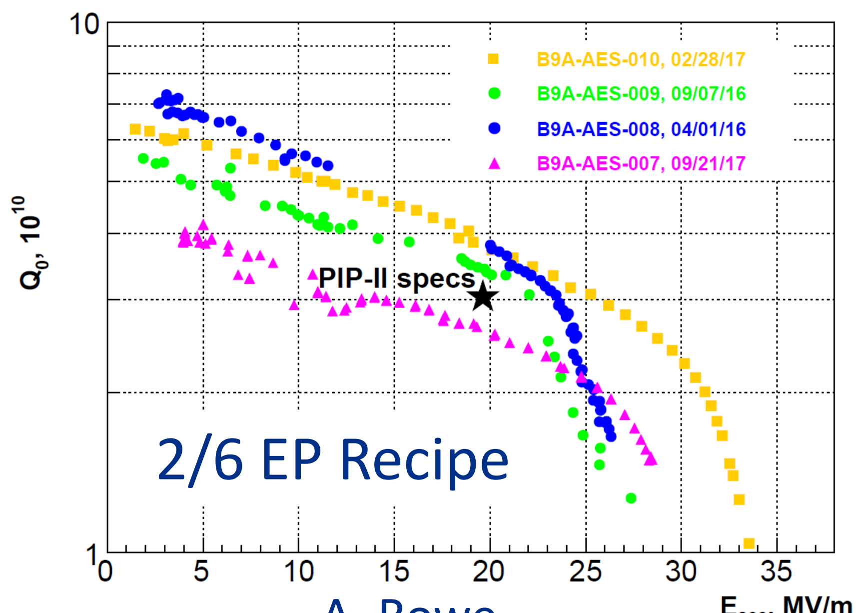
HB650 Cavity Production

- CM1
  - Four B.90 cavities - AES, Inc.
    - Prep & Test - FNAL/ANL
    - Dressing – FNAL
    - VTS and STC qualification
  - RF Coupler Prototypes - CPI
  - Two B.92 cavities/RF couplers – DAE
    - Prep & Test through HP testing – RRCAT
    - Qualification – FNAL VTS/STC
  - Three B.92 Prototypes – Qualified Vendor
    - Prep & Test – FNAL
    - Qualification HP testing – FNAL VTS/STC
- CMs 2-4
  - UK In-kind Cont.
  - STFC receives VTS-ready dressed cavities
    - Processing and jacketing at Vendor
  - RRCAT In-kind Cont.
    - DAE/Indian Industry
    - Ship to UK qualified





>64 kW, CW, full reflection

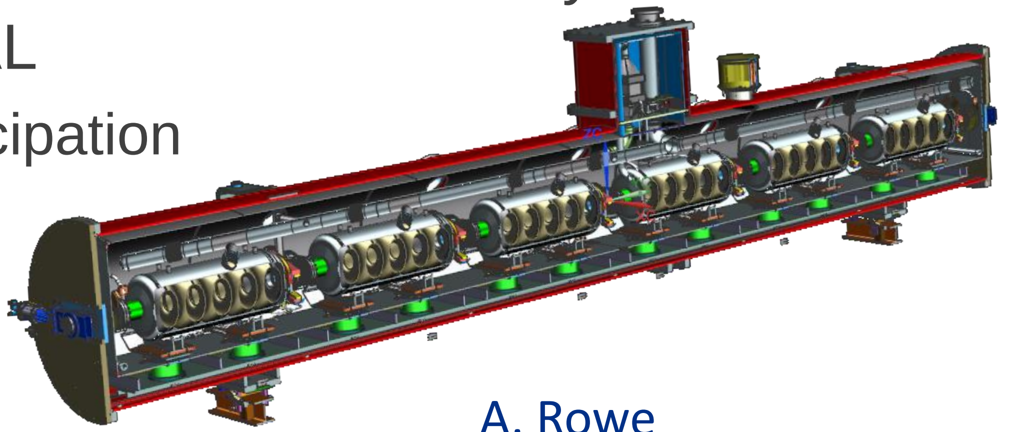


A. Rowe

Fermilab PIP-II

HB650 Cryomodule Fabrication Strategy

- CM1
  - Four B.90, two B.92 cavities in the string
  - String, coldmass, and string integration at FNAL (Lab2 or CAF)
  - Common tooling design and assembly approach to SSR1
  - US sourced components to the extent available
  - Staged alignment strategy (string, coldmass, final)
  - QA/QC activities (visual inspection, CMM, leak checks, etc.) for incoming components/sub-assembly are performed in TD at FNAL
  - STFC CM assembly participation



A. Rowe

HB650 Cryomodule Production

- CMs 2-4
  - STFC In-kind contribution planned
  - CM1 build establishes all production documentation (QA/QC, acceptance criteria, hold points, travelers, etc.)
    - Transferred to UK
    - UK versions developed for CMs 2-4
  - STFC Integration
    - FNAL participating in CM production – graded approach
    - Sourcing all components for CMs
    - Performing all internal acceptance and QC
    - ½ dressed & qualified cavities from the DAE
    - Ships completed CMs to FNAL
  - FNAL Quality Checks and ORC + Qualification testing

A. Rowe

Outline

- Introduction of PIP-II Cryomodules
- Cryomodule Design Overview
- Alignment Specification and Implementation
- Interfaces
- Assembly Tooling
- Heat Load and Cryogenics
- Design Verification
  - SSR1 CM#1 (S11)
  - HB650 CM#1 (H1)
- Lessons Learned, Risk and Schedule
- Summary

SRF Component Procurement Lessons Learned

- Avoid bitter procurement lessons of the recent past
  - RF Coupler procurements caused > 1 year delay in SSR1
- Minimize vendor technical development
  - Contract with proven vendors for critical procurements
- Minimize Schedule Risk
  - Track procurement cycles and progressive milestones at vendors
- Minimize Cost Risk
  - Seek multiple vendor bids
  - Carefully define scope and expectations in bid request packages
- Engage Procurement Professionals early in the process
- Willingness to reject non-conforming components

A. Rowe

Fabrication Risk Strategy

- Minimize in-process failures
  - Develop thorough fabrication and acceptance criteria
  - Insert hold and data review points in production
- Maximize vendor and Partner engagement
  - Visit vendors and Partners as often as required, in particular for first article production
- Establish technical ownership of production/contract
  - Cohesive relationship with FNAL Procurement, Technical Owner, and Vendor
- Fully integrate Quality Assurance Management Plan
  - Documentation requirements
  - Staff responsibilities

See A. Klebaner Presentation

A. Rowe

Integration Risk Strategy

- Interface Controls (ICDs, Interface Specs)
- Produce full suite of acceptance criteria
- Establish incoming QA/QC protocols and record keeping
- Execute on NCRs
- Develop inventory, handling, and routing procedures
- Implement assembly travelers and procedures for each sub-system and CM type
- Provide sufficient technical oversight of manual integrators
- Maintain CM integration redundancy.
  - Cryomodule repair
  - Back-up cryomodule production capability

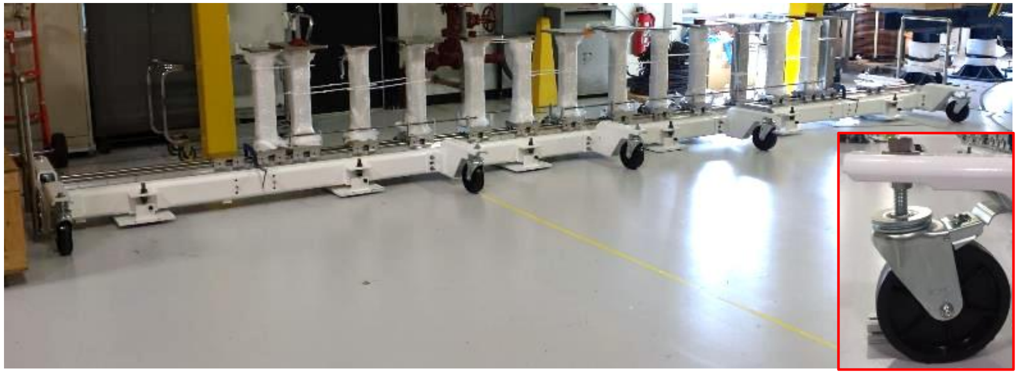
A. Rowe

Summary

- Cryomodule design standardization is a work in progress.
  - CM Standardization Workshop, September 4-7 in BARC, Mumbai.
- Integration of SSR1 CM1 and HB650 CM1 are critical to partner integration activities.
- PIP-II established a cryomodule development cycle
  - Components
  - Cryomodules
- CEA experience on cryomodule is a great contribution to PIP cryomodules
  - Clean room visits helped SSR1 assembly procedure development
  - Exchange of lessons learned from XFEL and LCLS-II can further improve PIP-II cryomodules

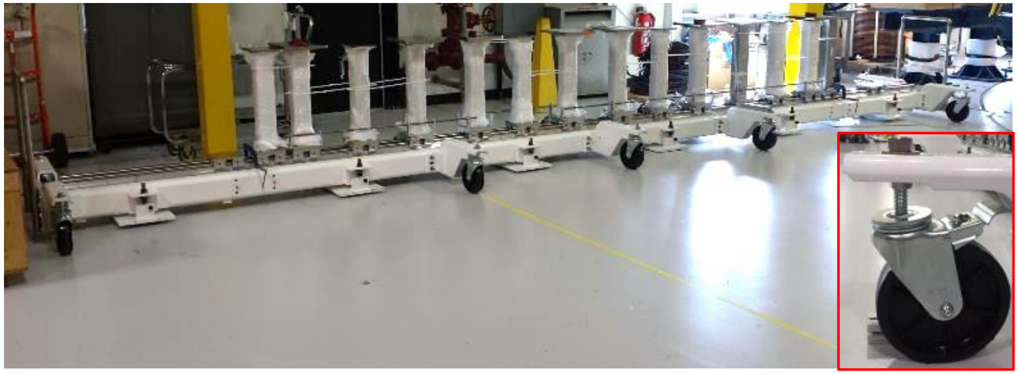
Backup Slides

Preparation of the SSR1 string assembly dry-run



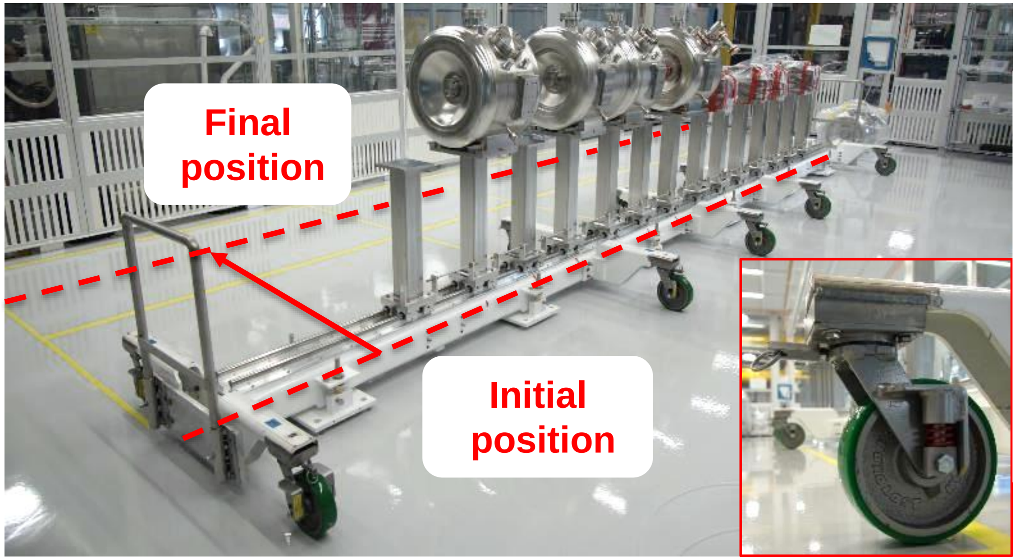
- Wheels were found to be inappropriate because of unexpected uneven floor
- Wheels lose contact with floor during motion leading to the wobbling of the rail system and excessive cavities displacements

Preparation of the SSR1 string assembly dry-run

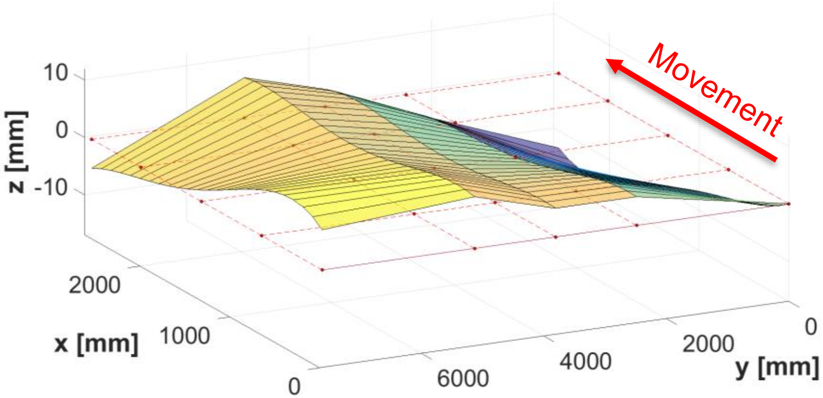


- Wheels were found to be inappropriate because of unexpected uneven floor
- Wheels lose contact with floor during motion leading to the wobbling of the rail system and excessive cavity displacements

- New suspension wheels and stiffer connections were procured
- Measurement of the cleanroom floor profile
- Wheel spring stiffness is optimized to minimize cavity vertical displacement



Cleanroom floor profile



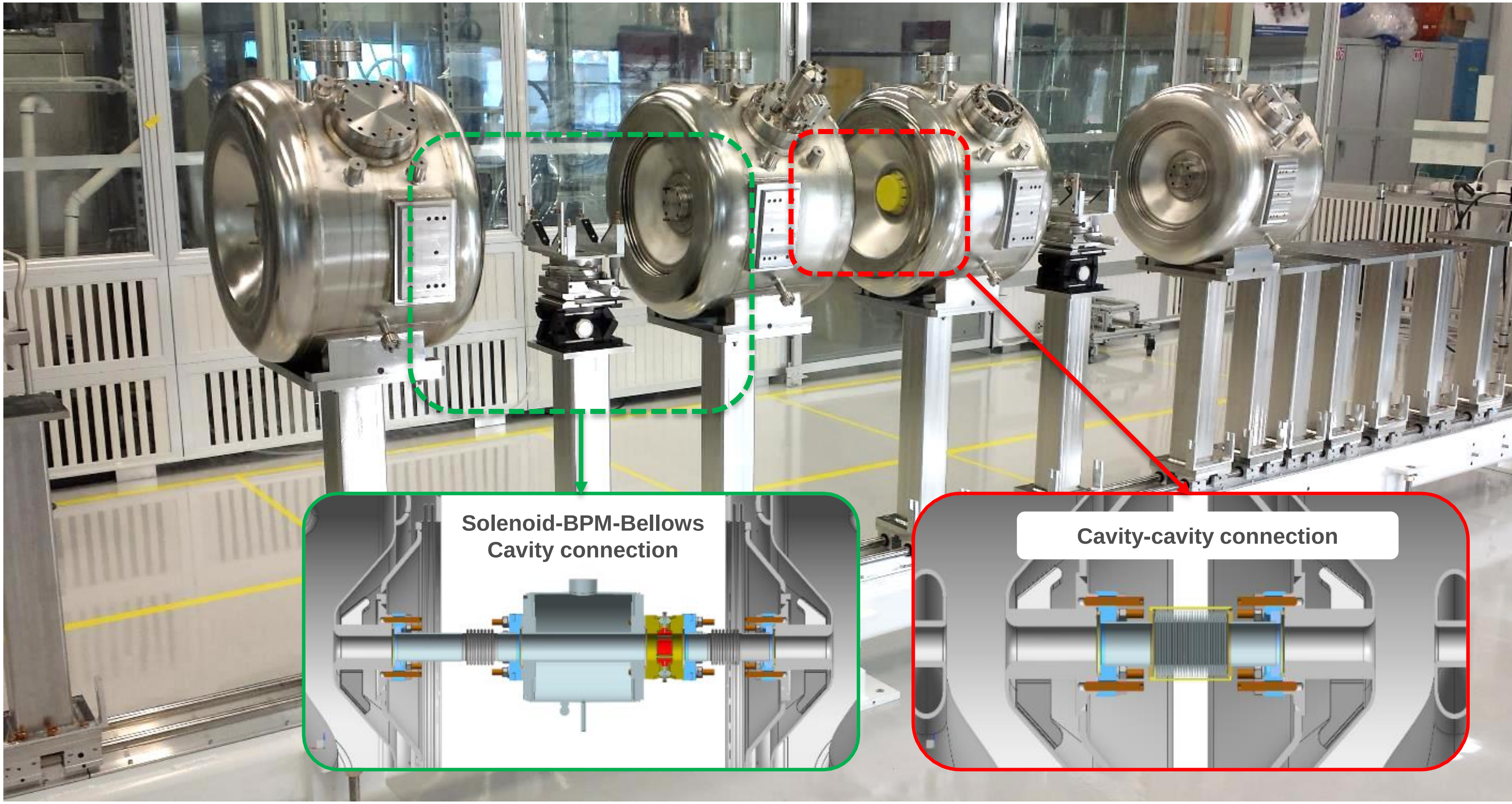
Preparation of the SSR1 string assembly dry-run Link

✓ Rail system with string weight can be successfully moved to the desired location. The process has been repeated 5 times and final position can be achieved with an uncertainty of ~ 5 mm

Preparation of the SSR1 string assembly dry-run

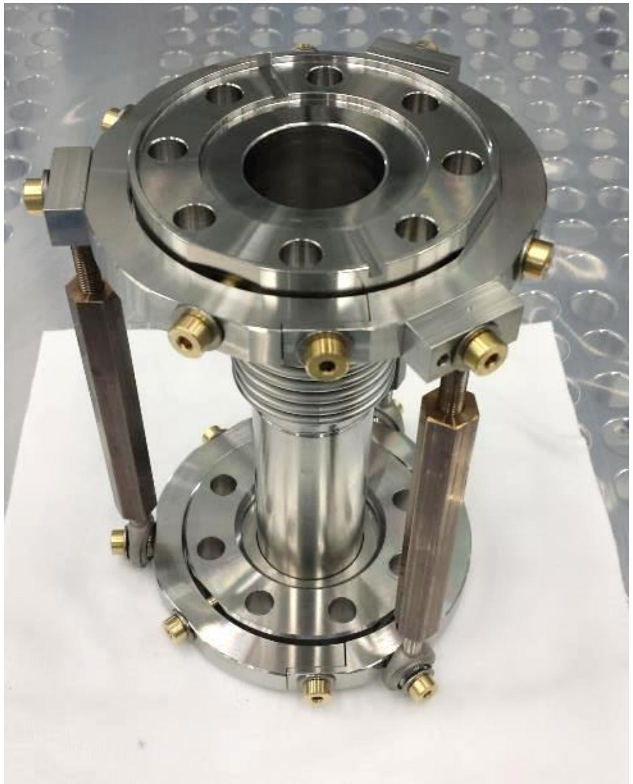
- Dry-run of SSR1 string assembly is carried out on a half cavity string
- The goal is to assess the feasibility of a cleanroom-compatible assembly

Preparation of the SSR1 string assembly dry-run



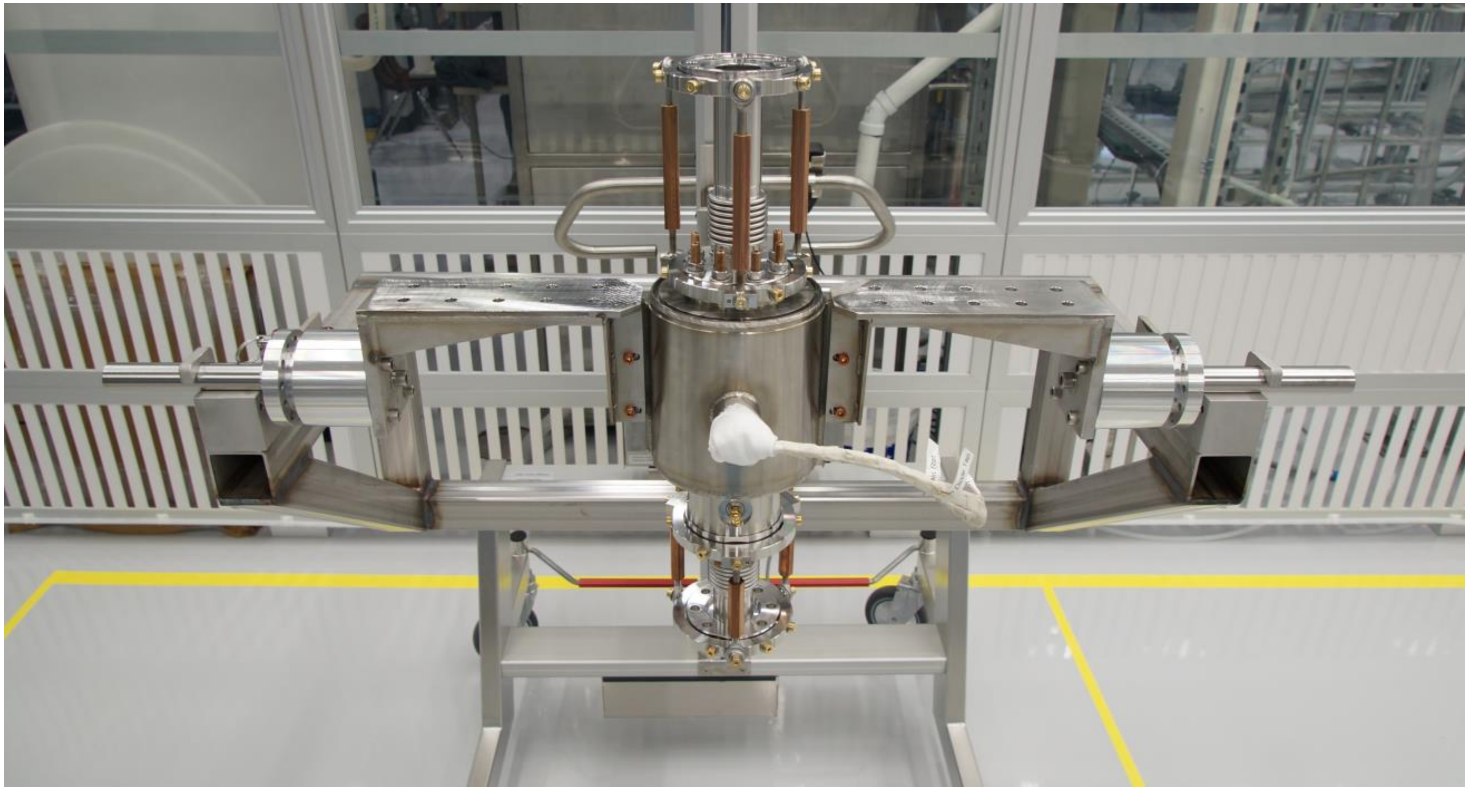
- Dry-run of SSR1 string assembly is carried out on a half cavity string
- The goal is to assess the feasibility of a cleanroom-compatible assembly

Preparation of the SSR1 string assembly dry-run



- ✓ Bellows cages provides 2 rotational degrees of freedom at the end flange
- ✓ Can be splitted in 2 halves so that can be removed prior cryomodule assembly

Preparation of the SSR1 string assembly dry-run



✓ Vertical assembly facilitates handling of components

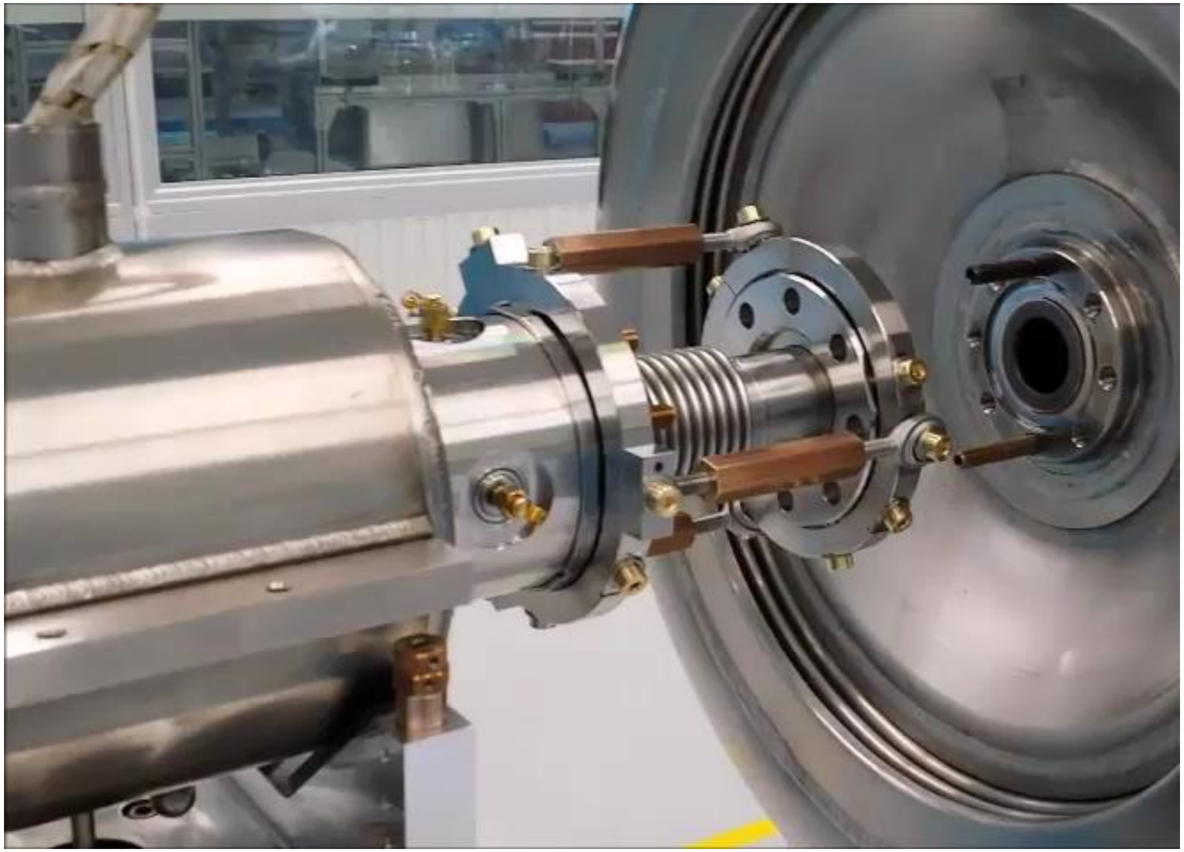
✓ Sub-assembly can rotate 360 degrees for an easy assembly

✓ The movable cart allows easy handling of the heavy sub-assembly

Preparation of the SSR1 string assembly dry-run

[Link]

Preparation of the SSR1 string assembly dry-run

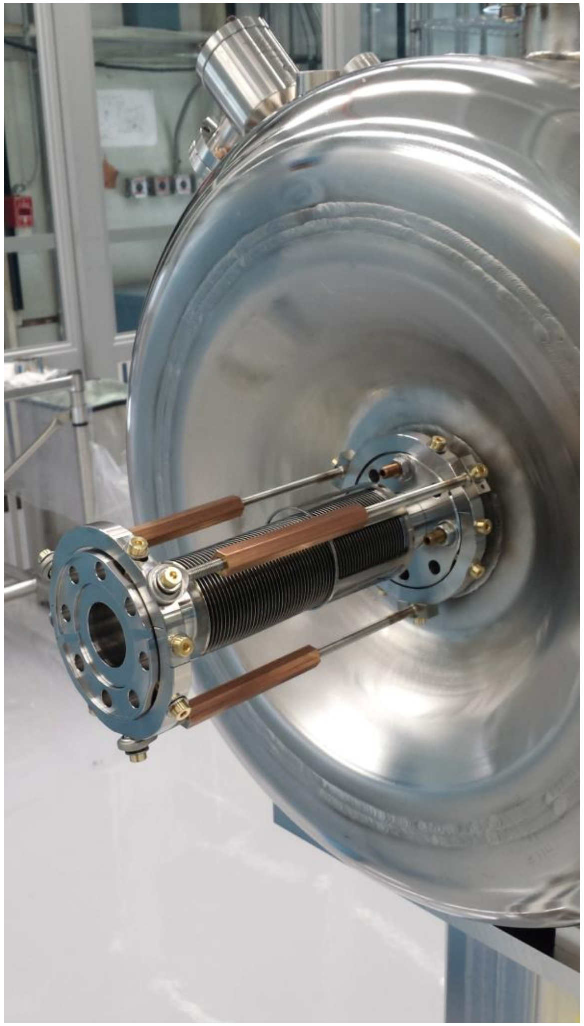


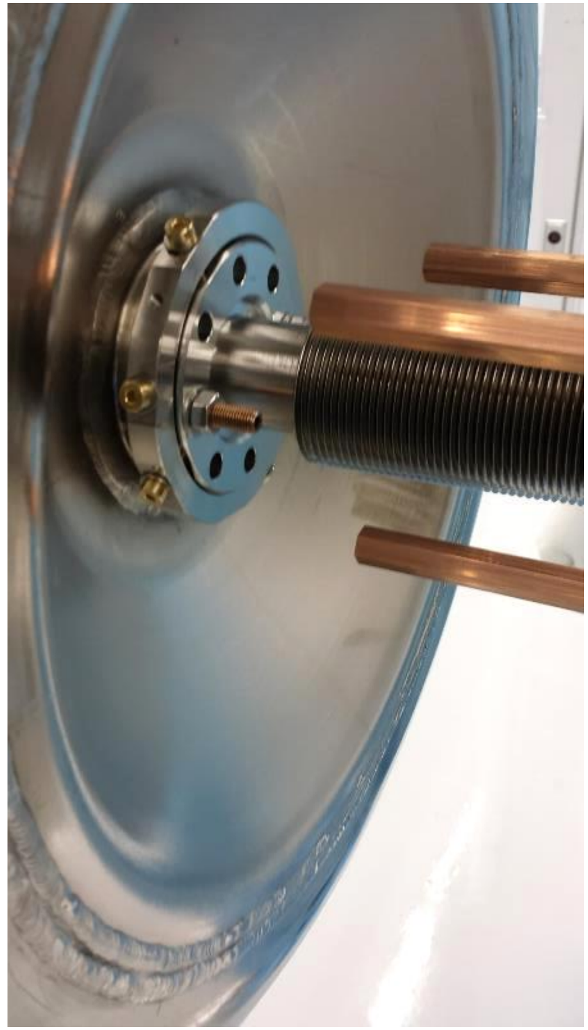
- ✓ Sub - millimeter precise and reliable alignment
- ✓ Easy to use system

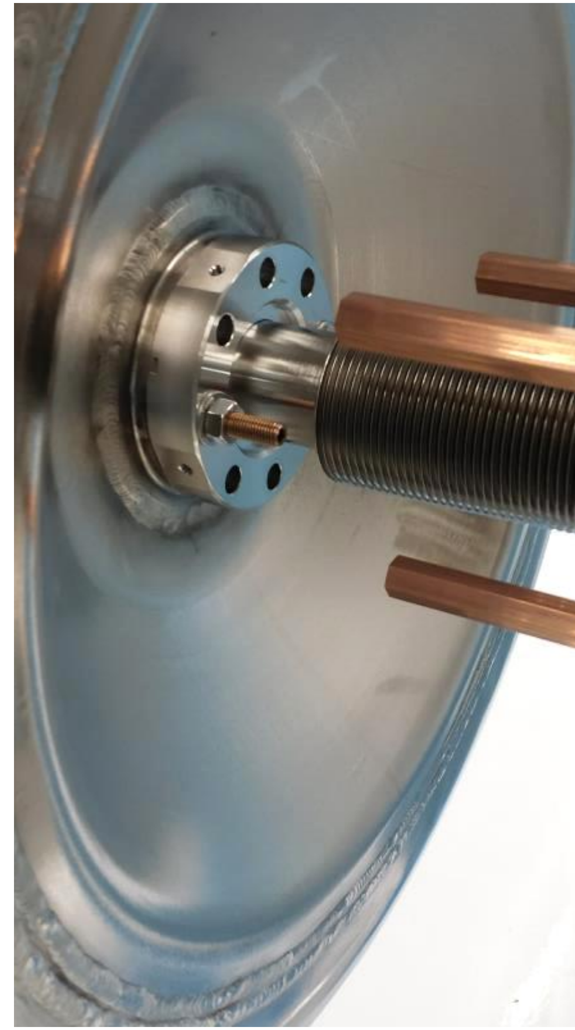
[Link]

Preparation of the SSR1 string assembly dry-run

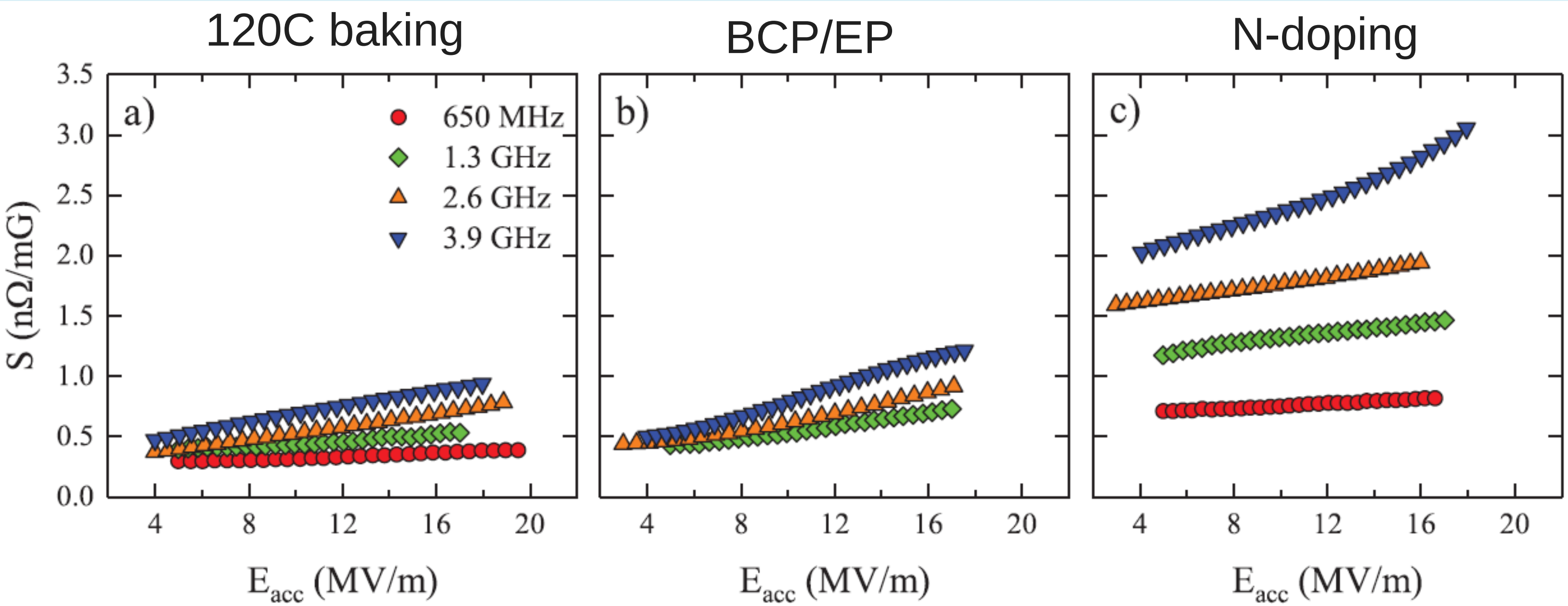
Bellows cage is disassembled once the cavity-cavity connection is completed







Sensitivity for different frequencies



- Trapped flux sensitivity increases with frequency
- The increment strongly depends on the surface treatment, i.e. on the mean free path
- Higher frequencies seem to have a larger field dependence

M. Checchin, M. Martinello et al., App. Phys. Lett. 112 072601 (2018)